LESS WORK AFTER SPACEFLIGHT: HUMAN PERFORMANCE BIOMECHANICS FOLLOWING ADAPTATION TO SIMULATED HYPOGRAVITY

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LESS WORK AFTER SPACEFLIGHT: HUMAN PERFORMANCE BIOMECHANICS FOLLOWING ADAPTATION TO SIMULATED HYPOGRAVITY

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This thesis is gratefully dedicated to:

My husband, Joseph L. Viteri,
my constant source of encouragement,
whose interests in all my ventures has never
been less than my own,

My mother, Sun M. Lee,
my constant source of love and patience,
who instilled in me the drive and motivation to
pursue any and all of my dreams,

And my brother, Justin Yun,
my constant source of laughter,
who... asked me to put him on this page.

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Per aspera ad astra.

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LIST OF SYMBOLS AND ABBREVIATIONS

1.0g	Earth's gravity
COM(z)	Center of mass (displacement in the z-direction)

SUMMARY

Within the next decade, humans will return to the Moon to establish a permanent presence and prepare for future explorations to Mars. Despite our intuitive knowledge of the influence of gravity, we still do not fully understand how our bodies develop, function, and navigate in hypogravity environments. This study aimed to evaluate the effect of reduced gravity on the biomechanical adaptation of countermovement jumping performance. Fifteen healthy participants performed targeted countermovement jumps in and out of simulated hypogravity using a reduced-gravity simulator that provided a constant upward force near the body's COM. This constant vertical force effectively reduced bodyweight by 50%, simulating ~0.5g during the vertical jumps. The countermovement jump was divided into two main phases: (i) the Lift phase (from countermovement initiation to take off) and (ii) the Land phase (from touchdown until the stabilization of ground reaction forces).

To better understand and investigate which specific parts of the Lift and Land were being affected by hypogravity adaptation, additional partitions were made. In chronological order, the parts of the Lift phase included the Early and Late Unloading phases and Early and Late Propulsive phases, and the Land phase included Early and Late Braking phases and Early and Late Recovery phases. In the first post-adaptation jump upon return to 1.0g, there was a meaningful effect in the normalized work of the Lift phase and a significant decrease in the net normalized work of the Land phase when compared to the baseline pre-adaptation jumps. Further investigation into the different portions of the jump revealed meaningful effects in specifically the last part of the Lift phase, i.e., the Late

Propulsive phase, and significant changes in the first part of the Land phase, i.e., the Early Braking phase. These results indicate that humans can adapt to simulated reduced gravity using this jumping adaptation paradigm. More interestingly, observations of normalized work on the COM before and after exposure to hypogravity revealed distinct control strategies for the Lift and Land portions of the countermovement jump. The work generated during the first parts of the Lift phase, i.e., the Unloading phases, appears to be dominantly controlled through a reactive strategy, as it showed no significant after-effects upon return to 1.0g. In contrast, the work generated during the Late Propulsive phase and absorbed during the Early Braking phase of the jump was observed to be predominantly under a predictive control strategy, evidenced by the significantly decreased work upon returning to 1.0g. Thus, upon return to a higher gravity level after exposure to hypogravity, movements requiring the legs to quickly generate and absorb energy will be most affected by sensorimotor control prediction errors. This would increase the likelihood of performance errors or even injury in actions that require rapid acceleration and deceleration of the COM and should be taken into consideration during the post-adaptation re-acclimation process after prolonged exposure to hypogravity.

CHAPTER 1. INTRODUCTION

By 2024, under the Artemis Program, the National Aeronautics and Space Administration will send the first woman and the next man to the surface of the Moon to establish a permanent presence and prepare humanity for future explorations to Mars [1]. As we enter this age of long-term spaceflight and habitation of outer space and other planets, it is essential to understand how our bodies adapt to and behave in heterogravity (i.e., gravity levels different from Earth) environments. Since the mid-twentieth-century, extensive studies on the effects of altered gravity have been conducted on Earth in preparation for lunar and, now, Martian expeditions. Despite our intuitive knowledge of the influence of gravity, we still do not fully understand how non-Earth's gravity levels affect our biological and physical processes.

1.1 Hypogravity Environments

Life on Earth evolved under the presence of a relatively constant gravity, which is essential for the development of neuromuscular behavior during locomotion [2]. Terrestrial organisms, including humans, have evolved significant features of their composition and functions to survive under Earth's gravity (1.0g). For example, the effect of gravity is well observed in organisms that entered terrestrial environments from aqueous environments where gravitational forces were largely counteracted by buoyancy [3]. This transition from water to land required new features including diminution of body size, development of extremities, the appearance of double blood circulation, increase in the heart weight due to larger energetic requirements on land, amongst others [3]. Environmental constraints, such as the constant force of Earth's gravity, are important in dictating the characteristics of terrestrial physiology.

Before humans try to establish permanent residence on the Moon and Mars in the near future, it is necessary to investigate if and how our bodies function, develop, and navigate in hypogravity environments. Bioastronautics research has shown that the following occurs to the human body in microgravity (~0g): decreased total intravascular volume which is maintained at this new homeostatic level; the heart becomes less elongated and lung volume is reduced because gravity is no longer providing a downward distending force; the distribution of both ventilation and blood flow in the lungs become more uniform; the heart and muscular component of the blood vessels atrophy because less force is required to move blood; eye anatomical and visual changes occur during long-duration spaceflight; post-flight motion sickness lasting from a few hours to more than a week; decreased strength in the major postural and limb skeletal muscles early muscle fatigability, poor balance, and potentiation of postural muscle reflexes; dysmetria, causing gait ataxia and frequently under or overshooting when reaching for an object; unilateral gaze nystagmus, which has been associated with dizziness and vertigo; and muscle, connective tissue, and skeletal atrophy [3, 4]. Countermeasure protocols were developed to counteract some of these adverse effects of stress on the human body in weightlessness. Therefore, it is essential to continue studying and developing options for countermeasures and possible life-support systems using simulated reduced gravity techniques on Earth before future long-duration space flights and interplanetary travel.

1.2 Simulated Reduced Gravity Methods and Studies

Simulated-hypogravity studies on Earth offer unique opportunities and insights to better understand performance in these unique conditions. Over the past century, numerous reduced gravity simulation techniques have been proposed and developed. Some of these methods include vertical motion devices, the use of aircraft, water submersion, and vertical cable suspensions, amongst others [5]. An example of a vertical motion device is a drop tower in which a payload is dropped from a high tower (e.g., one of NASA's drop towers is a 24.1m chamber). Drop towers operate on the principle that the payload in free fall is unaffected by gravity and, therefore, experiences weightlessness [6]. Although it is a simple method to simulate reduced gravity, vertical motion devices are not suitable for studies involving human locomotion, such as human gait [5]. An advantage to simulating reduced gravity using an airplane flying in a parabolic flight pattern is that it successfully negates gravity and allows for movements up to six degrees of freedom. However, parabolic flight has its disadvantages, such as limitations on data collection time, the unreliability of accurately measurable speeds, and frequent motion sickness in participants [5, 7]. Water immersion techniques, i.e., neutral-buoyancy simulations, where the participant is placed underwater and kept submerged using weights, are suitable for studying slow movements [5, 8]. However, some researchers have avoided using this method to study locomotion as frictional drag is induced on the limbs by the fluid medium [5, 8]. Vertical cable suspension systems use a gantry to gradually unweight a vertically suspended participant. One type of vertical cable suspension is with the participant in the upright position (as opposed to horizontal). An advantage to this system is that it is simple and suitable to study locomotion. Unfortunately, participants will have limited degrees of movement and gravity will only partially be negated as their limbs may experience 1.0g [5].

Similar to a vertical cable suspension system with the participant upright, the reduced gravity simulator used in the current study is intended to partially negate the net bodyweight force vector on the body center of mass (COM) through the use of constant-force springs (Fig. 2). For the purpose of this study, which was to investigate the effects of reduced gravity on locomotor adaptation in jumping, the reduced gravity simulator was the best suited to simulate hypogravity on the COM. Furthermore, unlike the other simulation techniques previously discussed, the reduced gravity simulator allowed for multiple jumping trials without limiting data collection times, concern of motion sickness in participants, and induced drag on the limbs.

There are advantages and disadvantages to all simulated-hypogravity simulations being performed on Earth. A common limitation is that each technique does not successfully simulate the fluid shifts and changes in blood flow that will occur in hypogravity conditions during space missions to the Moon or Mars. However, there is still much that can be gained by using these simulation techniques on Earth, including biomechanical issues that are of interest for long-duration space flight. Furthermore, experimenting with reduced gravity simulators on Earth helps better utilize the time spent in space [1].

Several studies utilizing hypogravity simulators have discovered decreases in human kinetic measures, including mechanical work, force [9], and power with reductions in gravity levels [5, 10, 11, 12]. Similarly, negative loading studies, using bodyweight support systems, have shown that negative loading alters movement kinematic patterns because of a change in resistance to active forces and through changes of the central neural command that adapt the pattern of muscle activation producing the optimal mechanical output [13]. Also, it has been established that gravity plays a crucial role in the selection of an efficient modality of locomotion. In running, gravitational forces play a greater role than inertial forces in determining appropriate alignment of the ground reaction force vector along the leg to provide efficient limb and joint kinetics [7]. In spaceflight, under the conditions of weightlessness, the most suitable mode of movement appears to be flotation, while on the Moon (1/6g), skipping and bouncing gaits are preferred [3, 10, 14]. Although much knowledge has been gained through studying the effects of simulated-hypogravity and microgravity on steady locomotor mechanics, less is known about the effects of hypogravity on biomechanical adaptations related to locomotor control.

1.3 Locomotor Adaptation

In the current study, I focus on the locomotor adaptation of sensorimotor control using a jumping paradigm. Locomotor adaptation describes a process of motor learning to alter movement in response to new yet predictable perturbations to the body or environment [15-17]. Neural adaptation of locomotion is driven by recalibrating a forward model, which is a representation of the motor system that uses information about a motor command and the current state of the motor system to predict the expected sensory outcome of a movement [15, 18]. A common example of a locomotor adaptation paradigm is using a split-belt treadmill, where participants walk with one leg moving faster than the other [15, 16]. When the movement is first perturbed in early adaptation, participants walk with an asymmetric stepping pattern with one leg's steps shorter than the other, producing a limping gait. During this phase, the participants sense a mismatch in the predicted sensory outcome and the actual outcome, signaling a sensory prediction error [19, 20]. These sensory prediction errors are what drive the recalibration of the forward model [19, 20]. As the participants continue to walk in this way, they begin to adapt their step length to re-establish a symmetric gait, essentially recalibrating their forward model to reduce movement errors. By late adaptation, participants exhibit near symmetric gait, i.e., equal step lengths. Post-adaptation, when participants walk with both legs at equal belt speeds, instead of immediately returning to the pre-adapted state, participants exhibit after-effects that reflect a newly stored sensorimotor calibration [20].

A similar process can be seen in countermovement jumps. In a study investigating the extent to which changes can influence motor and sensory adaptation in surface stiffness, Márquez et al. showed that after repetitive jumping on an elastic surface (adaptation phase), the first countermovement jump performed on a stiff surface showed an increase in leg stiffness and a decrease in jump height [21]. These after-effects could be the consequence of an erroneous internal model resulting from adaptation to the elastic surface [21]. In other words, these after-effects demonstrate that neural adaptation of the predictive locomotor control policy has occurred [15].

1.4 Feedback and Feedforward Control

Most motor adaptive behaviors, including stretch-shorten cycle movements (which will be discussed later in detail) and other natural movements, are governed by both feedback and feedforward processes [19, 20, 22, 23]. These two types of movement controls use sensory information differently. Feedback, or reactive, control uses sensory feedback during a motor task to activate muscles [22]. Reactive control involves integrations of peripheral inputs [19] to make on-line corrections as a movement unfolds [19, 20]. The second type of motor control is feedforward, or predictive, control. Motor commands issued under predictive control are planned in advance [22] and are not altered by on-line peripheral feedback [19], i.e., muscle contractions are executed based on sensory information that was gathered prior to movement initiation [22]. Thus, unlike reactive feedback control, corrections based on peripheral feedback are not possible while the movement unfolds in predictive feedforward control [19, 20]. Under ideal conditions, a system with perfect sensors providing accurate sensory feedback would only require a feedback controller to accurately respond to any external perturbations [24]. When sensory feedback is less reliable, the importance of feedforward control becomes apparent [24]. An example of predictive control can be seen in bouncing gaits [25] and countermovement jumps [26] when the lower limb muscles pre-activate prior to touchdown. Pre-activation of the lower limb muscles when jumping is important in preventing injuries by modulating levels of muscle stiffness in preparation for the land [10, 19]. Muscle pre-activation magnitude and timing, i.e., when muscles are activated prior to landing, are adjusted according to the prediction made prior to the movement and do not rely on sensory input gathered during the jump [26]. Furthermore, it is interesting to note that muscle pre-activation data has shown that adaptation of human locomotion can ensue under reduced gravity conditions [9, 26]. The current study further validates that biomechanical adaptation to hypogravity does occur in countermovement jumping and more interestingly, investigates which parts of the jump are most affected.

1.5 Countermovement Jumps and COM Work

The current study aimed to evaluate the effects of reduced gravity on locomotor adaptation by studying the biomechanical after-effects, specifically, the changes in COM work, in countermovement jumps. Many human movements such as running, jumping, hopping, and throwing involve a muscle action in which the desired motion is preceded by a movement in the opposite direction [19, 27], i.e., a countermovement. In a countermovement jump, the jumper starts in a static upright position (Figs 1a-1, 1b), makes a preparatory downward movement to the lowest COM position (Figs 1a-2.5, 1b) by flexing at the ankles, knees, and hips [13, 27], then immediately and vigorously extending the ankles, knees, and hips again to jump vertically off the ground (Figs 1a-3, 1d) [28]. This type of movement is one demonstration of when leg extensor muscles are likely to be undergoing a stretch-shorten cycle [13, 27, 28]. A stretch-shorten cycle describes the muscle function in which the pre-activated muscle is lengthened before shortening in the desired movement direction [10, 19, 20]. Similar to a spring, muscle lengthening has been shown to enhance force production and work output during the shortening of the muscles by partially releasing kinetic energy stored in the parallel and series elastic elements of the muscle-tendon unit [19, 27, 29]. Specifically, tendons store work done by the muscles then release it to power movement [29].

In addition to countermovement jumps, the capability to rapidly develop force during dynamic movements has been studied using drop jumps and squat jumps. In drop jumps, the jumper starts on a raised platform, drops to the ground continuing to lower their COM into a squat, then jumps vertically up. A recent study comparing the effects of countermovement jump and drop jump training found that countermovement jumps may be more effective in enhancing vertical jump height because of the slower stretch-shortening cycle [30]. In squat jumps, the jumper starts in a stationary semi-squat position then extends the ankles, knees, and hips to jump vertically up off the ground [27, 31], essentially removing the preliminary downward phase (i.e., the countermovement), and therefore, the lengthening and storing of kinetic energy. Thus, eliminating the countermovement results in diminished muscle activation, force production, and work output. Squat jumps are rarely used in practice and, when compared to countermovement jumps, the jumpers are not able to jump as high [27]. Additionally, it has been found that countermovement jump performance is almost always better in terms of power production and vertical height achieved than squat jump performance because countermovement jumps effectively utilize the stretch-shorten cycle [31]. The countermovement jump was selected for the current study for these reasons, and specifically, because (i) it is a natural human movement and (ii) ballistic movements such as countermovement jumps depend highly on predictive control [32].

The biomechanical metric used in this study to investigate the effects of hypogravity adaptation was work performed by the legs on the COM. Work was calculated by using the work loop technique [33], where a plot of the change in vertical ground reaction force (Figs 1d, 1e) and the vertical displacement of COMz (Figs 1b, 1c) over time provides a loop (Figs 1f, 1g). The area within the loop equals the work performed [13, 33, 34]. During the Lift phase of a countermovement jump, the lower limb muscles generate work to accelerate the body away from the ground, i.e., vertically displace the COM in reference to standing height, yielding a clockwise work loop (Fig. 1f). During the Land phase, the same muscles absorb work to decelerate the body, yielding a counterclockwise work loop (Fig. 1g). COM work has been used to study various areas of interest as it serves as a good representation of a global strategy for the movement of the body [13, 33, 34].

1.6 Current Study

In this study, participants were given an explicit task to jump vertically to a target that remained at a constant height throughout the entire protocol. They performed countermovement jumps in (i) 1.0g, (ii) simulated hypogravity of approximately 0.5g, and (iii) again at 1.0g. After hypogravity adaptation, I hypothesized that the normalized work done by the legs on the COM during the first post-adaptation jump would significantly decrease in magnitude compared to the pre-adaptation baseline jumps. By studying the after-effects of hypogravity adaptation, i.e., the changes in normalized work, I hope to provide additional insight into how humans may adapt to heterogravity environments and, more specifically, shed some light on the dominating control strategies used during different parts of a countermovement jump.

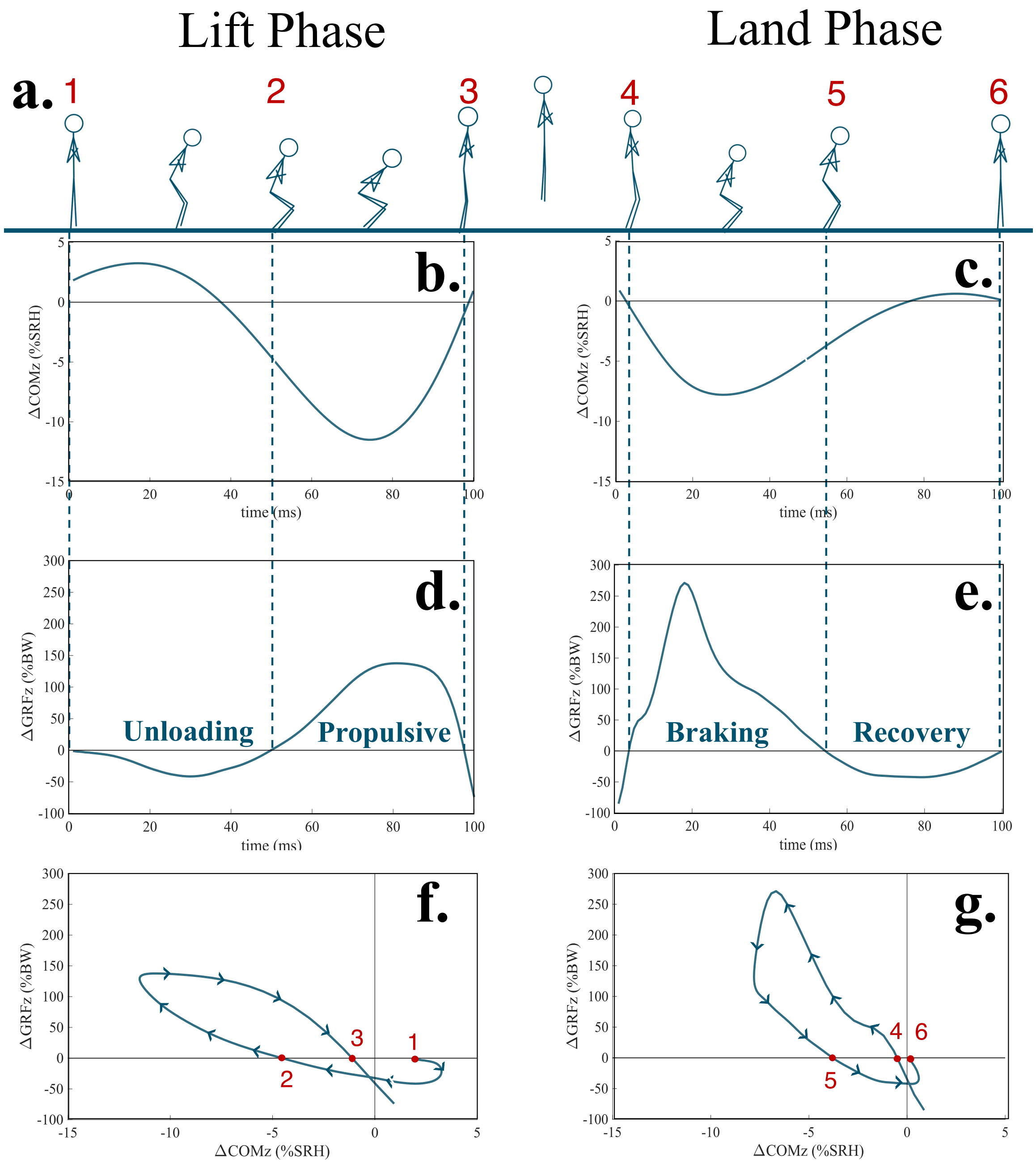

Figure 1 – Countermovement Jumps, Divisions, and Work Loops. (a.) Stick figures representing body configurations of the Lift and Land phases for a countermovement jump. (b.-e.) Example of kinematics (displacement of COM and change in vertical ground reaction forces) during the different phases of a countermovement jump. (d.-e.) Definitions of the different partitions of the Lift and Land phases – Unloading (from countermovement initiation to first crossing of the baseline vertical ground reaction force), Propulsive (from the end of Unloading phase to take off), Braking (from touch down first crossing of the baseline vertical ground reaction force), and Recovery (from the end of Braking phase to stabilization of vertical ground reaction force). (f.) Example of a work loop for the Lift phase the corresponding points (1-3) of the jump as seen in Fig.1a. (g.) Example of a work loop for the Land phase and the corresponding points (4-6) of the jump as seen in Fig.1a.

CHAPTER 2. METHODS

2.1 Participants

Fifteen healthy participants (8 male, 7 female; Table 1) took part in this study. Prior to participation, all individuals reviewed and signed informed consent per the protocol approved by the Georgia Institute of Technology Institutional Review Board (Protocol #H19325).

Participants were included in this study if they were between the ages of 18 and 69, had no history of major musculoskeletal injuries, had no history of major neuromuscular injuries, were able to jump, were free of any major cardiovascular, metabolic, respiratory, and renal diseases, and were fluent in English.

Participants were excluded from this study if they had dementia or were unable to sign informed consent, had significant immobility of the ankle, knee, and/or hip joints, or were pregnant.

Table 1 – Participant Demographics Information

Demographic	Mean ± Standard Deviation
Age	22.1 ± 3.7 yrs
Weight	617.7 ± 102.4 N
Height	173.9 ± 11.4 cm
Standing Reference Height	142.6 ± 9.2 cm
Max Jump Height	183.4 ± 15.0 cm
Target Height	173.2 ± 13.2 cm

2.2 Equipment

Kinematic and kinetic data were collected using an 8-camera 3D motion analysis system (Vicon Motion Systems, Oxford, UK) and two floor-embedded force plates (AMTI, Watertown, MA). These data were collected through Vicon Nexus and processed in Visual3D software (C-Motion, Germantown, MD). From this, biomechanical variables were calculated and compared across trials using custom MATLAB (The MathWorks, Inc. Natick, MA) scripts.

2.2.1 Reduced Gravity Simulator

A reduced gravity simulator, or bodyweight support system, was used to simulate hypogravity (Fig. 2). The reduced gravity simulator applies an upward, constant force to the participant's pelvis and torso near the COM using a modified rock-climbing harness. The harness was supported by four straps attached to a light aluminum frame above the participants' head, which kept the straps away from the participants' torso and did not hinder their ability to jump.

The constant-force springs provided a force that supported approximately half of the participants' bodyweight, effectively simulating a partial gravity environment. Different combinations of the springs were used to apply more or less force, allowing us to customize the system for each participant. Participants were asked to hold their arms across their chest to minimize the relative movement of the upper limbs, thereby better simulating reduced gravity.

2.2.2 *Real-time Visual Feedback System*

The real-time visual feedback system used for the experiment consisted of a monitor directly in front of the participants (Fig. 2), approximately 2.9 m away from the subject. The monitor (44”x24” dimensions) displayed a horizontal line indicating the target height and a bar that moved vertically, indicating the participant’s real-time height moving relative to the target.

2.3 Experimental Set-up

After completing the consent and questionnaire, the participants were asked to put on one of two modified rock-climbing harnesses depending on size and fit. Next, retroreflective markers for the motion capture system were placed on the participants in no particular order: sternal notch, vertebra C7, clavicle (2), rear shoulder (2), iliac crest (2), posterior superior iliac spine (2), anterior superior iliac spine (2), trochanter (2), a cluster of 4 markers on each thigh and shank, lateral knee (2), medial knee(2), lateral ankle (2), medial ankle (2), lateral foot (2), toe (2), heel (2) and metatarsophalangeal joints 1, 2, and 5 on each foot. Lastly, to determine which springs to use in the reduced gravity simulator, the participant’s height and weight were collected. The springs were chosen to pull up at a force approximately half of the participant’s bodyweight, resulting in a net downward acceleration that simulates half of Earth's gravity.

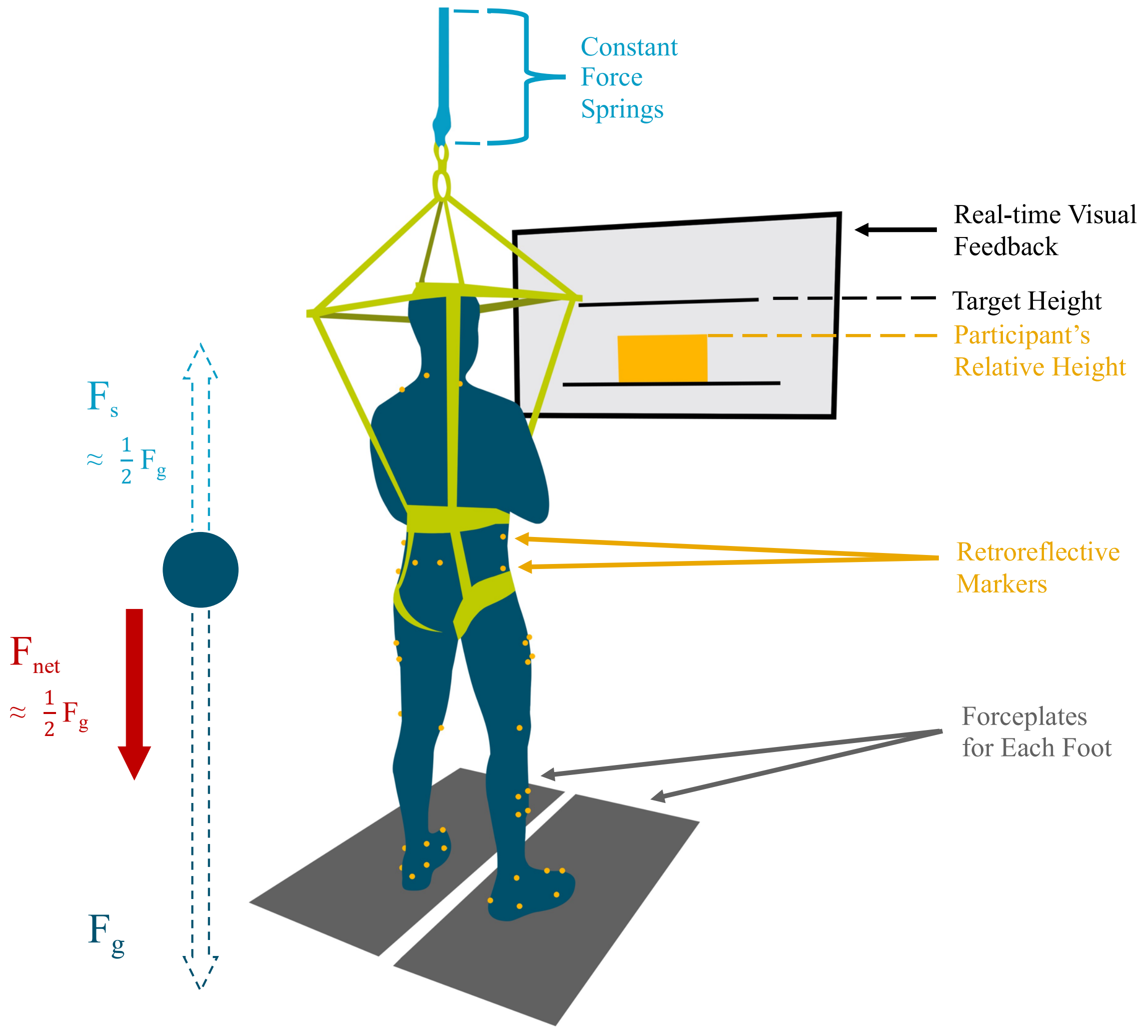

Figure 2 – Experimental Set-up. Reduced Gravity Simulator used to simulate ~0.5g (see free-body diagram on the left) during hypogravity adaptation jumps. Real-time Visual Feedback System was used to display target height (black line on the screen) and participant's relative vertical height (orange bar) during the performance of countermovement jumps (before, during, and after hypogravity adaptation).

2.4 Experimental Protocol

2.4.1 Calibration

Each experimental session began with a calibration trial that measured the participants' standing reference height (Table 1; determined by the sternal notch marker) and bodyweight while the participants stood as still as possible on the force plates.

2.4.2 Maximal Vertical Jumps

Participants crossed their arms and jumped as high as possible three times (Fig. 3) with sufficient rest between jumps. The highest vertical jump of the three was considered the maximal vertical jump height (Table 1, [35]). The target height (Table 1) used for the targeted jumps, i.e., sub-maximal jumps, was calculated as a percentage of the maximum height using Equation 1. The current study used targeted, sub-maximal jumps over maximal jumps throughout the entire protocol to avoid muscular fatigue and stress that could lead to possible injuries and because a targeted jump controls for variability in jump heights, and therefore, work done on the COM [35, 36].

$$\begin{aligned} &Target\ Height \\ &\quad = Standing\ Height \\ &\quad + [0.75 \times (Maxiumum\ Height\ -\ Standing\ Height)] \end{aligned} \tag{1}$$

The calculated target height was displayed to the participant via the visual feedback system (Sec. 2.2.2).

2.4.3 1.0g Pre-adaptation Jumps

For the pre-adaptation phase, the participants were instructed to jump, with their arms crossed, to hit the target displayed on the visual feedback system as accurately as possible. This was repeated for a total of ten trials with sufficient breaks in between jumps (Fig. 3). Participants were asked to try to land in such a way that they would avoid taking extra steps before or after the jump. Though not explicitly instructed, all participants used a countermovement leading into the jump. The data from the final three pre-adaptation jumps were averaged and used as a baseline control for statistical comparisons.

2.4.4 0.5g Hypogravity Adaptation Jumps

After completing the ten pre-adaptation jumps, the participants were placed in the reduced gravity simulator that pulled up at approximately half the participant's bodyweight. Another calibration trial was taken to measure reduced bodyweight and ensure that markers maintained the correct position after the harness shifted up. Similar to the pre-adaptation jumps, participants were asked to jump to the same target with their arms crossed. This was repeated for a total of 50 trials with sufficient rest as needed between jumps to avoid fatigue (Fig. 3).

2.4.5 1.0g Post-adaptation Jumps

Immediately following the last hypogravity adaptation jumps, participants were detached from the reduced gravity system and were instructed to perform ten post-training jumps immediately with the same instructions as baseline and training trials. Following the post-training jumps, a final calibration trial was taken (Fig. 3). The data from the first post-adaptation jump were used for statistical comparisons.

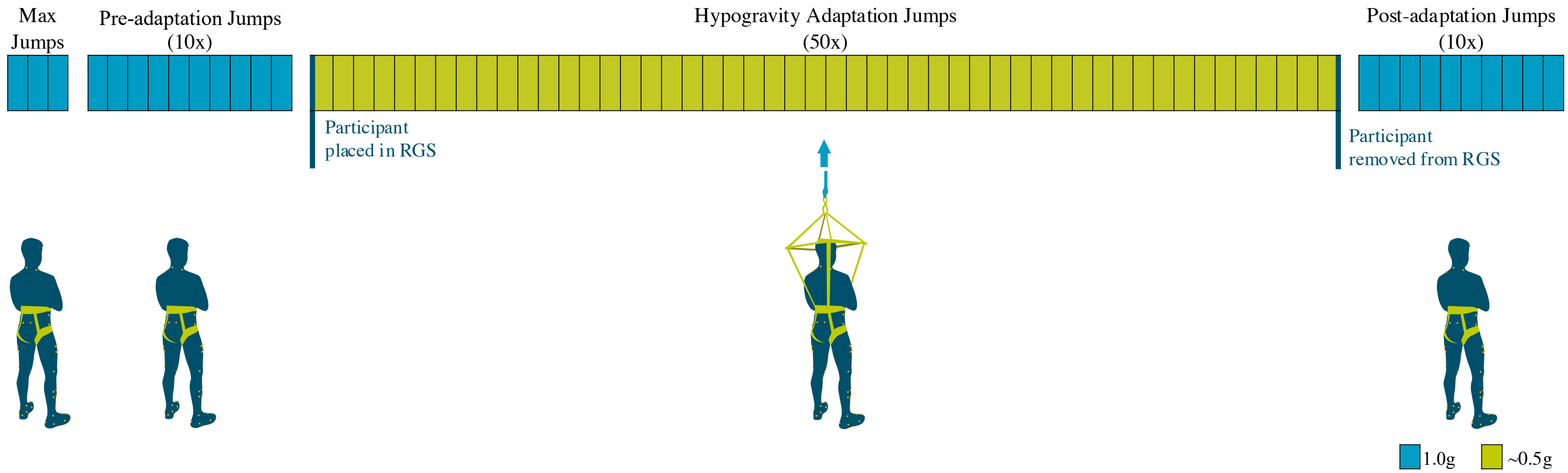

Figure 3 – Experimental Paradigm. The experiment consisted of four distinct stages: (i) the max jump stage, (ii) the pre-adaptation stage, (iii) the hypogravity adaptation stage, and (iv) the post-adaptation stage. Following the experimental set-up and preparation of the participant, participants performed maximal countermovement jumps. Locomotor adaptation was then performed in stages (ii-iv), where the participant jumped to a target in and out of the reduced gravity simulator (RGS). Stage (ii) consisted of 10 pre-adaptation jumps in 1.0g (blue), stage (iii) consisted of 50 hypogravity adaptation jumps in ~0.5g (green), and stage (iv) consisted of 10 post-adaptation jumps in 1.0g (blue). In between and throughout the four stages, participants were allowed sufficient rest.

2.5 Data Analysis

2.5.1 Countermovement Jumps

Lowpass filters were applied to markers and force signals (cutoff frequency of 25 Hz). The beginning (takeoff) and end (touchdown) of the aerial phase of the countermovement jump were determined using the force plate data with a threshold of 10 N for each leg. The beginning of the Lift phase was determined by countermovement initiation, defined as when the vertical ground reaction force was less than standing bodyweight. The aerial phase began and ended at take-off and touchdown, respectively. The remainder of the jump after touchdown until the vertical ground reaction force stabilized near bodyweight was determined as the Land phase. Specifically, the trial cut-off was defined as when the vertical ground reaction force equaled to bodyweight for the third time. To better understand and investigate which parts of the countermovement jump were being affected by hypogravity adaptation, partitions of the Lift and Land phases were made.

The first divisions of the countermovement jump were made at the bodyweight crossings. For the Lift phase (Fig. 1d), the negative area under the vertical ground reaction forces curve (below bodyweight) determined the Unloading phase, and the Propulsive phase was determined by the positive area (above bodyweight). Similarly, for the Land (Fig. 1e), the positive area under the curve determined the Braking phase, and the negative area determined the Recovery phase.

The second divisions of the countermovement jump were created by taking each phase's time duration and dividing them in half to produce the early and late partitions. For example, the early Unloading phase is the first temporal half of the entire Unloading phase, and the Late Unloading phase is the latter half.

2.5.2 Work Loops

The work loop technique was used to determine the normalized work output of the lower limbs during countermovement jumps [33]. Work loops (Figs 1f, 1g) were generated by plotting the vertical displacement of the COM (COMz; Figs 1b, 1c) normalized to the participant's standing height by the change in vertical ground reaction forces (Figs 1d, 1e) normalized to the participant's bodyweight. Net normalized work was calculated by taking the area inside the work loop using the cumulative integration function in MATLAB. The normalized COM work done during the Unloading phase was calculated by taking the area from the beginning of the jump to baseline vertical ground reaction force (Fig. 1f, point 1 to point 2). For the Propulsive phase, work was calculated by integrating from the end of the Unloading phase to the end of the Lift phase (Fig. 1f, point 2 to point 3). Similarly, the work done during the Braking phase was calculated by taking the area from touchdown (i.e., beginning of Land) to baseline vertical ground reaction force (Fig. 1g, point 4 to point 5). Lastly, work done during the Recovery phase was calculated by integrating from the end of the Braking phase to the end of the Land (Fig. 1g, point 5 to point 6). The work for the early phase for each division was calculated by taking the area from the beginning of each phase to half of that phase's total duration. For the late phases, the integral was taken from the half of the total duration of that phase to the end of the phase.

2.6 Statistical Analysis

For all variables (net normalized work and subsequent divisions), a two-tailed Student's paired t-test (alpha = .05) was used to determine statistical significance between the baseline pre-adaptation jumps and the first post-adaptation jump. Assumptions for the t-test, normality of distribution, and equivalence of variances were tested using the Shapiro-Wilk's test and Levene's test, respectively. If one or both assumptions were violated, a nonparametric test called the Wilcoxon Signed-Rank test was used to calculate p-values in place of the t-test. Statistical significance was set as $p < .05$.

2.6.1 Participant Exclusions

Out of 15 participants, three were excluded due to the reasons listed below:

1. Participant max jump height exceeded the limits of our reduced gravity simulator during jumps
2. Participant had extended pauses mid-way during the countermovement of the post-adaptation jump
3. Unexpected data loss of the Recovery phase

2.6.2 Post-hoc Power Analysis

Post-hoc power analysis was conducted, and the effect size was calculated using G*Power, the statistical power analysis tool [37]. Specifically, the effect size was calculated using Cohen's d effect size estimator. A common convention of the effect sizes suggested by Cohen are small ($d = 0.2$), medium ($d = 0.5$), and large ($d = 0.8$) [38]. See tables in Appendix.

CHAPTER 3. RESULTS

3.1 Net Normalized COM Work

Adaptation to reduced simulated gravity was associated with decreases in the magnitude of net normalized work only during the Land (Figs 4b, 4d) phases and not the Lift (Figs 4a, 4c) phases following hypogravity adaptation (Fig. 4, Table 2). The net normalized work of the first post-adaptation jump during the Lift phase did not meet the assumption of normality of the distribution required to perform a t-test (Shapiro-Wilk's test, $p = 0.033$, Table A.1). Therefore, a Wilcoxon Signed-Rank test was conducted to find no statistically significant difference ($p = 0.053$; d = 0.65; % change = -9.76%) in normalized work between the first post-adaptation jump ($\overline{W}_{POST,\ Lift} = 7.32 \pm 1.27\%$; means ± S.D.) and the average of last 3 pre-adaptation jumps ($\overline{W}_{PRE,\ Lift} = 8.11 \pm 1.08\%$) of the Lift (Figs 4a, 4c). The average of last 3 pre-adaptation jumps and the first post-adaptation jump work of the Land met both assumptions for the t-test and results revealed significant reduction ($p < 0.001$; d = 1.29; % change = -16.8%) in the first post-adaptation jump ($\overline{W}_{POST,\ Land} = -8.39 \pm 1.09\%$) compared to the average of last 3 pre-adaptation jumps ($\overline{W}_{PRE,\ Land} = -10.1 \pm 1.32\%$).

Table 2 – Values for the mean and standard deviation of normalized work, percent change between the baseline pre-adaptation jumps and the first post-adaptation jump, *p*-values, and Cohen's d for the effect size for the first division of phases.

PRE (baseline pre-adaptation jumps) vs. POST (first post-adaptation jump) (n = 12)

Phases	PRE (%)		POST (%)		Change (%)	*p*	Cohen's d
	Mean	STD	Mean	STD			
Lift							
Net	8.113	1.084	7.321	1.271	-9.756	0.0531	0.6533
Unloading	-4.082	2.216	-3.375	1.760	-17.319	0.0783	0.5590
Propulsive	12.195	1.963	10.696	1.648	-12.287	0.0531	**1.1518****
Land							
Net	-10.080	1.324	-8.386	1.093	-16.808	**0.0009***	**1.2925****
Braking	-13.220	1.689	-10.537	1.494	-20.295	**< 0.001***	**2.0392****
Recovery	3.141	0.680	2.152	1.040	-31.488	**0.0172***	**0.808****

*** $p < 0.05$**

**** d ≥ 0.8**

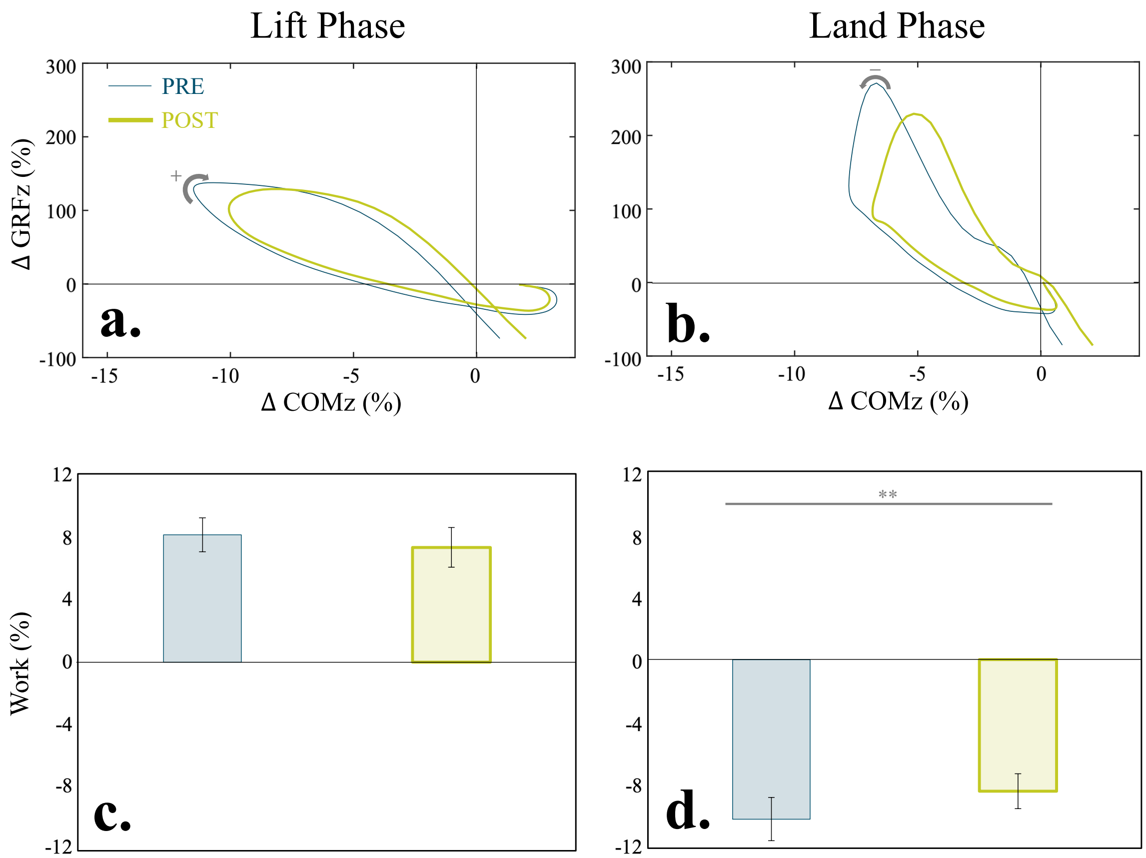

Figure 4 – Net Normalized Work of Lift and Land Phases. (a.-b.) Work loops for the Lift and Land phases, respectively, plotted as the displacement of the COM in the z-direction by the change in vertical ground reaction forces. The thinner blue line represents the average work loop of the baseline pre-adaptation jumps. The thicker green line represents the average work loop of the first post-adaptation jump. (c.-d.) The bar graphs display the normalized work means of the baseline pre-adaptation (blue) and post-adaptation (green) jumps. Error bars represent the standard deviations. (** represents p-values < .01 and * represents p-values < .05)

3.2 First Divisions of the Countermovement Jump – Baseline Vertical Ground Reaction Force Crossings

For the Lift phase, there were no significant differences in the Unloading and Propulsive phases of the Lift (Fig. 5c, Table 2). The net work of the baseline pre-adaptation jumps during the Unloading phase did not meet the assumption of normality of the distribution required to perform a t-test (Shapiro-Wilk's test, p = 0.002, Table A.1). Therefore, a Wilcoxon Signed-Rank test was conducted to reveal no statistical significance (p = 0.078; d = 0.56; % change = -17.3%) in net normalized work between the first post-adaptation jump ($\overline{W}_{\text{POST, Unloading}}$= -3.38 ± 1.76%) and baseline pre-adaptation jumps ($\overline{W}_{\text{PRE, Unloading}}$ = -4.08 ± 2.22%). Similarly, the net normalized work of the first post-adaptation jump during the Propulsive phase did not meet the assumption of normality of the distribution required to perform a t-test (Shapiro-Wilke's test, p = .021, Table A.1) and the Wilcoxon Signed-Rank test was conducted to reveal no statistical significant difference (p = 0.053; d = 1.15; % change = -12.3%) in net normalized work between the first post-adaptation jump ($\overline{W}_{\text{POST, Propulsive}}$ = 10.7 ± 1.65%) and the baseline pre-adaptation jumps ($\overline{W}_{\text{PRE, Propulsive}}$ = 12.2 ± 1.96%).

As for the Land phase, significant decreases between the baseline pre-adaptation jumps and the first post-adaptation jump of the Braking and Recovery phases of the Land were observed (Fig. 5d, Table 2). The baseline pre-adaptation jumps and the first post-adaptation jump work of the Braking phase met both assumptions for the t-test and results revealed significant reduction (p < 0.001; d = 2.04; % change = -20.3%) in the first post-adaptation jump ($\overline{W}_{\text{POST, Braking}}$ = -10.5 ± 1.49%) compared to the baseline pre-adaptation jumps ($\overline{W}_{\mathrm{PRE,\ Braking}}$ = -13.2 ± 1.69%). Similarly, the work of the baseline pre-adaptation jumps and the first post-adaptation jump of the Recovery phase met both assumptions for the t-test and results revealed significant reduction (p = 0.017; d = 0.80; % change = -31.5%) in the first post-adaptation jump ($\overline{W}_{\mathrm{POST,\ Recovery}}$= 2.15 ± 1.04%) compared to the baseline pre-adaptation jumps ($\overline{W}_{\mathrm{PRE,\ Recovery}}$ = 3.14 ± 0.680%).

Table 3 – Values the for mean and standard deviation of normalized work, percent change between the baseline pre-adaptation jumps and the first post-adaptation jump, *p*-values, and Cohen's d for the effect size for the second division of phases.

PRE (pre-adaptation baseline jumps) vs. POST (first post-adaptation jump) (n = 12)

Phases		PRE (%)		POST (%)		Change (%)	*p*	Cohen's d
		Mean	STD	Mean	STD			
Lift								
Unloading	Early	1.226	2.894	1.456	2.799	18.735	0.6856	0.1200
	Late	-5.308	1.510	-4.831	1.752	-8.989	0.3445	0.2852
Propulsive	Early	-10.597	4.776	-9.255	3.301	-12.661	0.1656	0.4287
	Late	22.791	3.700	19.951	3.310	-12.461	0.0690	**0.9224****
Land								
Braking	Early	-18.990	3.029	-16.093	2.534	-15.256	**0.0017***	**1.1861****
	Late	5.770	2.101	5.556	2.202	-3.710	0.6650	0.1156
Recovery	Early	2.603	0.634	2.611	0.898	0.294	0.6236	0.0089
	Late	0.537	0.261	-0.459	0.948	-185.518	**0.0007***	**1.1777****

*** $p < 0.05$**
**** d ≥ 0.8**

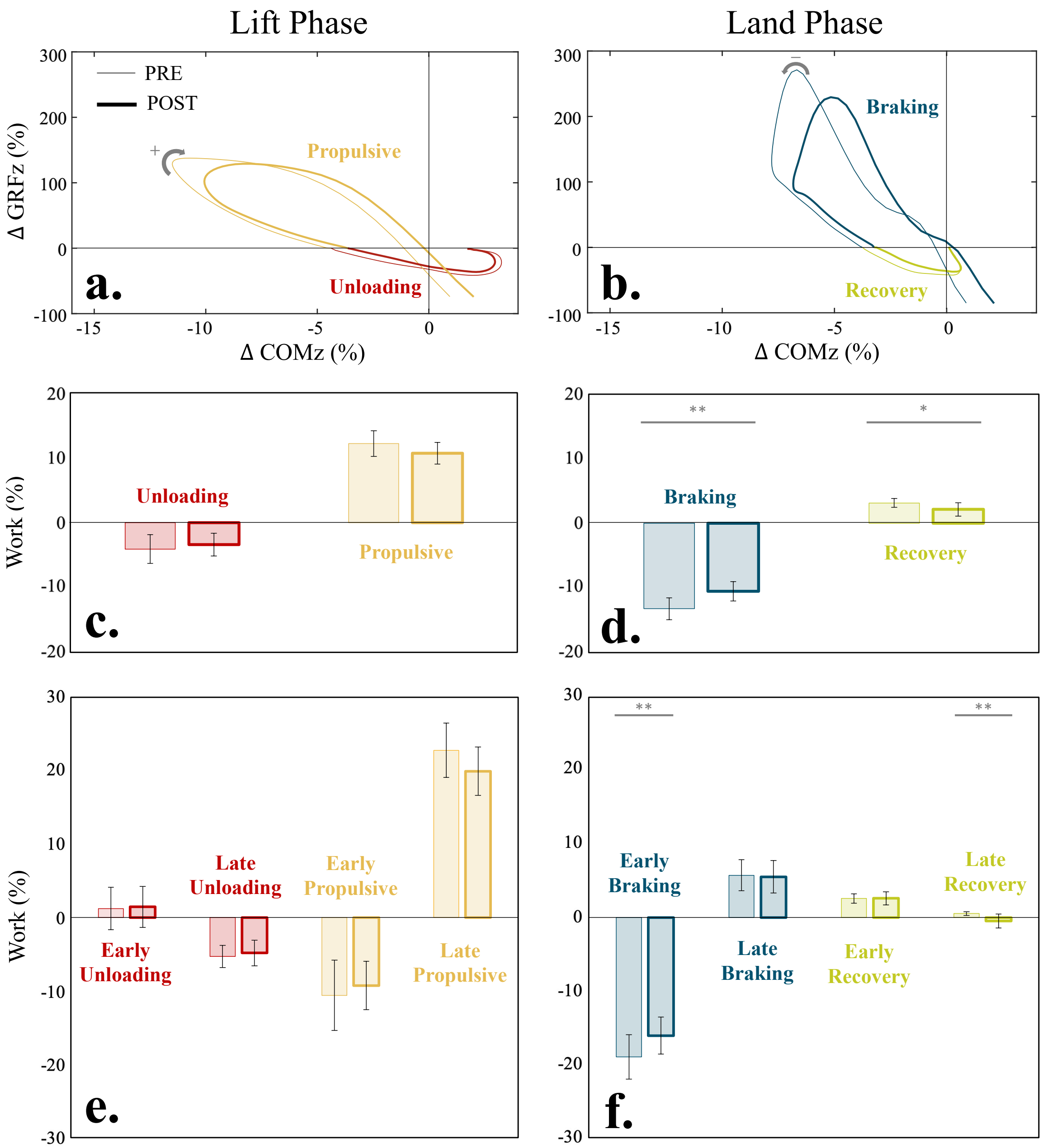

Figure 5 – Net Normalized Work for First and Second Divisions of Lift and Land Phases. (a.-b.) Work loops for the Lift and Land phases, respectively, plotted as the displacement of the COM in the z-direction by the change in vertical ground reaction forces. The thinner line represents the average work loop of the baseline pre-adaptation jumps. The thicker line represents the average work loop of the first post-adaptation jump. The parts of the loop in red represents the Unloading phase; orange represents the Propulsive phase; blue represents the Braking phase; and green represents the Recovery phase. (c.-f.) The bar graphs display the net normalized work of the baseline pre-adaptation (bar with thinner outline) and post-adaptation (bar with thicker outline) jumps during each phase. Error bars represent the standard deviations. (** represents p-values < .01 and * represents p-values < .05)

3.3 Second Divisions of the Countermovement Jump – Temporal Halves

For the Lift phase, there were no significant differences in the Early and Late Unloading and Early and Late Propulsive phases (Fig. 5e, Table 3). The baseline pre-adaptation jumps and the first post-adaptation jump work of the Early Unloading phase met both assumptions for the t-test and revealed no statistically significant difference (p = 0.686; d = 0.12; % change = 18.7%) in the first post-adaptation jump ($\overline{W}_{\text{POST, Early Unloading}}$ = 1.46 ± 2.80%) compared to the baseline pre-adaptation jumps ($\overline{W}_{\text{PRE, Early Unloading}}$= 1.23 ± 2.89%). Similarly, the baseline pre-adaptation jumps and first post-adaptation jump work of the Late Unloading phase met both assumptions for the t-test and revealed no statistically significant difference (p = 0.344; d = 0.29; % change = -8.99%) in the first post-adaptation jump ($\overline{W}_{\text{POST, Late Unloading}}$ = -4.83 ± 1.75%) compared to the baseline pre-adaptation jumps ($\overline{W}_{\text{PRE, Late Unloading}}$ = -5.31 ± 1.51%). For the Early Propulsive phase, the baseline pre-adaptation jumps and the first post-adaptation jump work met both assumptions for the t-test and revealed no statistically significant difference (p = 0.166; d = 0.43; % change = -12.6%) in the first post-adaptation jump ($\overline{W}_{\text{POST, Early Propulsive}}$ = -9.25 ± 3.30%) compared to the baseline pre-adaptation jumps ($\overline{W}_{\text{PRE, Early Propulsive}}$ = -10.6 ± 4.78%). Lastly, the net normalized work of the first post-adaptation jump during the Late Propulsive phase did not meet the assumption of normality of the distribution required to perform a t-test (Shapiro-Wilke's test, p = 0.039, Table A.1). Therefore, a Wilcoxon Signed-Rank test was conducted to reveal no statistical significance (p = 0.069; d = 0.92; % change = -12.5%) in net normalized work between the first post-adaptation jump ($\overline{W}_{POST,\ Late\ Propulsive}$ = 20.0 ± 3.31%) and the baseline pre-adaptation jumps ($\overline{W}_{PRE,\ Late\ Propulsive}$= 22.8 ± 3.70%).

For the Land phase, there were significant differences in the Early Braking and Late Recovery phases and no significant differences in the Late Braking and Early Recovery phases (Fig. 5f, Table 3). The baseline pre-adaptation jumps and the first post-adaptation jump work of the Early Braking phase met both assumptions for the t-test and revealed a statistically significant difference (*p* = 0.002; d = 1.19; % change = -15.3%) in the first post-adaptation jump ($\overline{W}_{POST,\ Early\ Braking}$ = -16.1 ± 2.53%) compared to the baseline pre-adaptation jumps ($\overline{W}_{PRE,\ Early\ Braking}$= -19.0 ± 3.03%). However, the net normalized work of the first post-adaptation jump during the Late Braking phase did not meet the assumption of normality of the distribution required to perform a t-test (Shapiro-Wilk's test, *p* = 0.042, Table A.2). Therefore, a Wilcoxon Signed-Rank test was conducted to reveal no statistically significant difference (*p* = 0.665; d = 0.12; % change = -3.71%) in net normalized work between the first post-adaptation jump ($\overline{W}_{POST,\ Late\ Braking}$= 5.56 ± 2.20%) and the baseline pre-adaptation jumps ($\overline{W}_{PRE,\ Late\ Braking}$ = 5.77 ± 2.10%). Similarly, the net normalized work of the first post-adaptation jump during the Early Recovery phase did not meet the assumption of normality of the distribution required to perform a t-test (Shapiro-Wilk's test, *p* = .020, Table A.2). Therefore, a Wilcoxon Signed-Rank test was conducted to reveal no statistically significant difference (*p* = 0.624; d = 0.009; % change = 0.29%) in net normalized work between the first post-adaptation jump ($\overline{W}_{POST,\ Early\ Recovery}$ = 2.61 ± 0.898%) and baseline pre-adaptation jumps ($\overline{W}_{PRE,\ Early\ Recovery}$ = 2.60 ± 0.63%). For the Late Recovery phase, the net normalized work of the first post-adaptation jump did not meet the assumptions of normality of the distribution (Shapiro-Wilk's test, $p = 0.015$, Table A.2) and equivalent variances (Levene's test, $p < 0.001$, Table A.2) required to perform a t-test. Therefore, a Wilcoxon Signed-Rank test was conducted to reveal statistically significant difference ($p < 0.001$; d = 1.18; % change = -185.5%) in net normalized work between the first post-adaptation jump ($\overline{\mathrm{W}}_{\mathrm{POST,\ Late\ Recovery}}$ = -0.459 ± 0.948%) and the baseline pre-adaptation jumps ($\overline{\mathrm{W}}_{\mathrm{PRE,\ Late\ Recovery}}$ = 0.537 ± 0.261%).

CHAPTER 4. DISCUSSION

4.1 Summary of Findings

This study aimed to evaluate the biomechanical effects of adaptation to simulated reduced gravity. I hypothesized that immediately following simulated-hypogravity adaptation, the net normalized work of the Lift and Land phases of the subsequent post-adaptation jump would significantly decrease in magnitude. I found that during the Lift phase of the countermovement jump, there was no statistically significant difference in work observed between the pre-adaptation baseline jumps and the first post-adaptation jump conditions. However, as predicted, there was a statistically significant reduction in normalized work done during the Land phase of the countermovement jump following adaptation to simulated reduced gravity. The following subsections list the main findings of the different Lift and Land phases of the countermovement jump in chronological order.

4.1.1 Lift Phases of Countermovement Jump

- Early Unloading: no significance and small effect size
- Late Unloading: no significance and small effect size
- Early Propulsive: no significance and small effect size
- Late Propulsive: no significance and large effect size

4.1.2 *Land Phases of Countermovement Jump*

- Early Braking: significant and large effect size
- Late Braking: no significance and small effect size
- Early Recovery: no significance and small effect size
- Late Recovery: significant and large size effect

4.2 Adaptation to Hypogravity

To better understand how hypogravity adaptation affects human performance, we examined the changes in net normalized work done on the COM during targeted countermovement jumps. When first jumping in reduced gravity, participants seldom hit the target they jumped to during the pre-adaptation phase. This could be caused by discrepancies between the predicted and actual neuromuscular demands of the jump, signaling a sensory prediction error [15, 32]. Sensory prediction errors drive a recalibration of the forward model [15, 18, 32] to predict the jump's sensorimotor outcomes. Possible sensory prediction errors that drove the forward model’s recalibration during the countermovement jumps in this study could be the combination of failed or successful acquisition of the target (visual feedback) and muscle force generation and lengthening (proprioceptive feedback). Throughout 50 hypogravity adaptation jumps, participants were likely updating their forward model using these sensory prediction errors via predictive changes in their jumps [15, 18, 32]. Intuitively, when participants adapted during the hypogravity jumps, the first post-adaptation jump was expected to be lower in both displacement of COMz and vertical ground reaction force. As predicted, there was a statistically significant reduction of normalized work in the Land phase. However, the reduction in normalized work for the Lift phase was borderline significant and had a medium effect size (Table 2). Therefore, a possible interpretation could be that, although there was no significant difference between the pre-adaptation baseline jumps and the first post-adaptation jump in the Lift phase, it could be underpowered, and therefore, the effect could still be meaningful. Therefore, it can be concluded that immediately following hypogravity adaptation, when the participants were removed from the reduced-gravity simulator (i.e., back at 1.0g), participants continued to jump as if they were in simulated-partial gravity as seen by the decrease in net normalized work of the Lift and Land phases of the first post-adaptation jump (Fig. 4).

Although target acquisition remained variable with no statistically significant changes before, during, and after hypogravity adaptation, the reductions in work of the Lift and Land phases can be considered to be a convincing after-effect of successful jumping adaptation, reflecting the newly stored sensorimotor calibration and indicating that the recalibrated forward model prediction of jumping in reduced gravity was stored [15]. In other words, the described changes in normalized work data suggest adaptation to reduced gravity occurred.

4.3 Feedback and Feedforward Control in Targeted Countermovement Jumps after Hypogravity Adaptation

Predictive feedforward control is a type of movement control where muscle contractions are planned in advance and executed based on sensory information gathered prior to the movement [19, 22, 32]. It is often associated with an internal model of the central nervous system, which controls motor output and predicts the factors associated with and the consequences of that movement [22]. Feedback or reactive control is the second type of movement control that processes peripheral feedback to contract muscles while performing a motor task [19, 22, 32]. It is important to note a critical difference between reactive and predictive controllers. Reactive control can use peripheral feedback to make corrections that might be necessary as the movement unfolds; however, predictive control typically remains unchanged by peripheral feedback [19, 22, 32].

It may be counterintuitive to observe that the earlier phases of the Lift are not meaningfully affected as the countermovement of the first post-adaptation jump was the first motor action completed by the participants upon returning to 1.0g. A possible explanation as to why the Early and Late Unloading and Early Propulsive phases of the Lift were less impacted by adaptation, i.e., had no statistically significant after-effect, could, in part, be due to the predominant reactive control over them. One simple example of reactive responses is the monosynaptic stretch reflex [19], which is a homonymous, rapid muscular contraction that occurs in response to passive stretch applied to the muscle. In this way, excitatory length feedback from leg extensor muscles may be responsible for appropriate modulation of the muscles during the early parts of the countermovement jump. Ankle, knee, and hip joints all undergo flexion during the controlled descent of the countermovement, which would result in a passive stretch of the extensor muscles. Excitatory, autogenic feedback from these muscles could then provide appropriate modulation of muscle activation to accommodate any unexpected increase in gravity on the first post-adaptation jump.

As shown by our data, on average, participants' predictions of how much work is required to reach the target were off and variable following hypogravity adaptation. This is likely a consequence of successfully adapting their countermovement jumps in a reduced gravity environment and using the sensory information collected from these jumps to predict the first post-adaptation jump back in 1.0g. This ultimately led to meaningful reductions in work of the Late Propulsive and Early Braking phases when compared to the other phases. For the Late Propulsive phase, the reduction in normalized work was just slightly over the significance threshold and had a large effect size (Table 3). This could mean that, although not statistically significant in terms of the p-value, the large effect size may denote that there is still a meaningful effect. Therefore, a possible explanation as to why the last part of the Lift showed a not significant but meaningful effect of hypogravity adaptation could be because of the dominant feedforward control at play. During propulsion in locomotion, when the leg joints are extending, most muscles are undergoing active shortening at a high velocity to produce the power needed for the jump. When muscles are activated concentrically (i.e., when muscle fascicles shorten), muscle spindles, which detect the changes in length of a muscle, are less sensitive to length feedback [39]. This could explain why the Late Propulsive phase appears to be more influenced by a predictive control strategy. Furthermore, it is well-known that ballistic movements such as countermovement jumps depend greatly on feedforward control [13], and more specifically, it could be the Late Propulsive phase of the countermovement jump that is highly dependent on feedforward control. Consistent with this, Taube et al. [19] described that for stretch-shortening cycle movements such as drop jumps, the predictive controller plans the movement and predicts factors such as time of ground contact, muscle pre-activation, and sensitivity of spindle fibers, amongst others. Depending on the situation and task, the central nervous system adjusts its activity. At the instant of first ground contact, peripheral feedback will be generated and further integrated into the rest of the jump (reactive control).

It is interesting to note that the Early Propulsive phase exhibited a low significance but did not go below the significance threshold, and the effect size fell within the upper region of the small effect size range, i.e., it was close to transitioning into the medium effect size range (Table 3). A possible explanation of the results may be that, following the Unloading phase and prior to the Late Propulsive phase, there could be a conversion happening during the Early Propulsive phase from a feedback dominated control in the earlier parts of the Lift (Early and Late Unloading phases) to a feedforward dominated control in the last part of the Land (Late Propulsive phase). Therefore, the data from this study could be reflecting that conversion.

After the aerial phase of the countermovement jump, the first part of the Land (Early Braking phase) was observed to be notably more sensitive to hypogravity adaptation than any other phase. This was shown by the statistically significant adaptation-associated reduction in the magnitude of the work done in the first post-adaptation jump (Figs 5e, 5f; Table 3). The Late Braking and Early Recovery phases, which occur after the initial touchdown, were not significantly impacted by hypogravity adaptation. Therefore, a similar interaction between predictive and reactive control in the Lift can be seen in the Land. Landing during movements such as hopping or drop jumps is characterized by three main stages [12]. The first stage occurs during the aerial phase and is identified by the predictive [12] pre-activation of the muscles prior to landing. The second stage is characterized by muscle stretching, or the eccentric muscle action, which is seen in the Early Braking phase. The last stage is attributed to the muscles' concentric action, seen in the Late Braking and the Early and Late Recovery phases. It has been shown that the first stage and part of the second stage are predominantly under predictive motor control, and part of the second stage and third stage are under reactive motor control [12], which is consistent with our findings. However, contrary to the literature, the data from this study found no moderate or large significance in the differences between the baseline pre-adaptation jumps and first post-adaptation jump of the Late Braking phase, indicating that by this time of the Land the control system may have already converted to a predominantly feedback mechanism.

Lastly, although there was a statistically significant change in the normalized work of the Late Recovery phase, however, it was not experimentally controlled. Participants could have been continuing to stabilize or oscillate or may have stumbled or taken a step in response to returning to 1.0g, so although it was significant, it may not be meaningful.

After the first post-adaptation jump, the error feedback, which largely influences learning and adaptation, between the predicted and the actual consequences of the jump was used to recalibrate the forward model. The forward model then readjusted the motor output using the new information from the past post-adaptation jump by altering the predictive command [19, 32] for subsequent post-adaptation jumps. In this way, participants in our study readapted back to the 1.0g environment quickly. It has been shown that predictive motor responses generally occur rapidly and require information about one miscalculated jump to calibrate appropriately [20].

4.4 Hybrid Feedback-Feedforward Control System

Prior to the initiation of the movement, the predictive feedforward control system planned the factors involved with the countermovement jump. During the COM's descent in preparation for the concentric phase (when muscles are active), peripheral feedback was generated, and the earlier parts of the Lift phase were seen to be under a predominant feedback control. Then, during the Early Propulsive phase there was a conversion of dominantly feedforward to dominantly feedback mechanisms in the control of the countermovement jump. We saw in the Late Propulsive phase that a meaningful effect was present as shown by the large effect size and therefore concluded that it was predominantly governed by feedforward mechanisms. Upon landing, I found significant work reductions between the baseline pre-adaptation jumps and first post-adaptation jump of the Early Braking signifying the operation of dominant feedforward control. Although these significantly affected phases were found to be predominantly under feedforward mechanisms, we cannot completely rule out feedback control as it may still in some ways be contributing to the movement. However, since there was still a significant after-effect, it could be concluded that the peripheral feedback from the proprioceptive, vestibular, and visual systems did not seem to be enough to entirely correct for the prediction made prior to the jump.

When investigating the roles of the feedforward and feedback controls, it was shown that purely feedforward systems and purely feedback systems are sensitive to unexpected disturbances and measurement errors, respectively [24]. Given the weaknesses of both the extremes and the likely presence of unexpected disturbances and measurement errors in any biological system, a hybrid feedforward-feedback system has been shown to be less sensitive to the disturbance and measurement noises that affect the purely feedforward and purely feedback systems [24]. Kuo demonstrated that for dynamical systems subject to both disturbances and measurement noise, (such as the hypogravity environment in my study) there is an optimum level of combined feedforward and feedback that results in better performance than either feedforward or feedback systems alone [24]. Therefore, in a study such as mine where the participant is subject to unexpected disturbances and measurement errors when jumping in and out of hypogravity to a target, there could be a combination of feedforward control with feedback control that reduces steady-state errors [24]. Thus, instead of a purely feedforward or feedback control at different parts of the countermovement jump, it is more likely that a hybrid feedforward-feedback control system is modulating the movement.

CHAPTER 5. CONCLUSION

The current study aimed to evaluate the effect of reduced gravity on the biomechanical adaptation during targeted countermovement jumps. Specifically, upon adapting to hypogravity, it was hypothesized that the normalized work of the Lift and Land phases of the countermovement jump would significantly decrease in magnitude after exposure to hypogravity when compared to jumps performed prior to hypogravity exposure. In the first post-adaptation jump upon return to 1.0g, there was a meaningful effect in the normalized work of the Lift and a significant decrease in the Land when compared to the baseline pre-adaptation jumps. Further investigation into the additional parts of the Lift and Land revealed meaningful effects in specifically the Late Propulsive phase, i.e., last part of the Lift, and significant changes in the Early Braking phase, i.e., first part of the Land. These results revealed that (i) humans can adapt to simulated hypogravity using the jumping adaptation paradigm proposed in this study and more interestingly, (ii) the distinct control strategies for the Lift and Land portions of the countermovement jump. The work performed on the COM during the first parts of the Lift phase was observed to be under reactive control, as it showed no significant after-effects, i.e., no statistically significant decrease in work magnitude, upon return to normal 1.0g. On the contrary, the work generated during the Late Propulsive phase and absorbed during the Early Braking phase was observed to be predominantly under a predictive control strategy, evidenced by the significant reduction of work performed on the COM upon returning to 1.0g. Therefore, after hypogravity exposure, energy absorbing movements will be most affected by sensorimotor control prediction errors, which can increase the likelihood of performance errors or injury in motor tasks that require deceleration from a jump, run or a fall and should be taken into consideration during the post-adaptation re-acclimation process. Hypogravity studies such as this (via simulations created on Earth) should continue to be conducted to advance our knowledge of the adaptability of the human motor system for future interplanetary explorations.

APPENDIX A. SUPPLEMENTARY TABLES

A.1 – Values for the mean, standard deviation, Shapiro-Wilk Test (test for normality), Levene's test (test for variance equivalence), p-values (using t-test or Wilcoxon Signed-Rank test), correlation coefficients, effect size, post-hoc power analysis for the Lift Phase

N = 12			Mean	Standard Deviation	Shapiro-Wilk	Levene's	p-values using t-test / non-par test	Correlation	Effect Size	Post-hoc Power
LIFT	Unloading	PRE	-0.04082	0.02216	0.00183	0.94956	0.07825	0.82156	0.55903	0.42380
		POST	-0.03375	0.01760	0.21259					
	Early Unloading	PRE	0.01226	0.02894	0.21023	0.35741	0.68565	0.77419	0.11999	0.06676
		POST	0.01456	0.02799	0.06860					
	Late Unloading	PRE	-0.05308	0.01510	0.69426	0.99137	0.34447	0.48218	0.28516	0.14752
		POST	-0.04831	0.01752	0.07259					
	Propulsive	PRE	0.12195	0.01963	0.05505	0.41500	0.05310	0.75373	1.15179	0.95183
		POST	0.10696	0.01648	0.02087					
	Early Propulsive	PRE	-0.10597	0.04776	0.39653	0.98370	0.16564	0.75836	0.42867	0.27369
		POST	-0.09255	0.03301	0.24692					
	Late Propulsive	PRE	0.22791	0.03700	0.94865	0.81812	0.06896	0.61915	0.92242	0.82823
		POST	0.19951	0.03310	0.03900					
	Net	PRE	0.08113	0.01084	0.21151	0.87501	0.05310	0.48003	0.65332	0.54143
		POST	0.07321	0.01271	0.03343					

A.2 – Values for the mean, standard deviation, Shapiro-Wilk Test (test for normality), Levene's test (test for variance equivalence), p-values (using t-test or Wilcoxon Signed-Rank test), correlation coefficients, effect size, post-hoc power analysis for the Land Phase

N = 12			Mean	Standard Deviation	Shapiro-Wilk	Levene's	p-values using t-test / non-par test	Correlation	Effect Size	Post-hoc Power
LAND	Braking	PRE	-0.13220	0.01689	0.29557	0.94386	0.00002	0.66439	2.03921	0.99999
		POST	-0.10537	0.01494	0.82465					
	Early Braking	PRE	-0.18990	0.03029	0.98322	0.97395	0.00173	0.62728	1.18614	0.96162
		POST	-0.16093	0.02534	0.55638					
	Late Braking	PRE	0.05770	0.02101	0.38368	0.98944	0.66501	0.63059	0.11561	0.06555
		POST	0.05556	0.02202	0.04258					
	Recovery	PRE	0.03141	0.00680	0.09030	0.44663	0.01730	0.03274	0.80808	0.72222
		POST	0.02152	0.01040	0.94376					
	Early Recovery	PRE	0.02603	0.00634	0.06153	0.31393	0.62360	0.40901	0.00889	0.05009
		POST	0.02611	0.00898	0.02000					
	Late Recovery	PRE	0.00537	0.00261	0.13597	0.00009	0.00073	0.50698	1.17766	0.95937
		POST	-0.00459	0.00948	0.01474					
	Net	PRE	-0.10080	0.01324	0.18700	0.63137	0.00094	0.42450	1.29252	0.98216
		POST	-0.08386	0.01093	0.36858					

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